

The Composite Load Spectra Project

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Abstract

The objective of the composite load spectra project is to develop probabilistic methods and generic load models capable of simulating the load spectra that are induced in space propulsion system components. Four engine component types (the transfer ducts, the turbine blades, the liquid oxygen posts and the turbopump oxidizer discharge duct) were selected as representative hardware examples. The composite load spectra that simulate the probabilistic loads for these components are typically used as the input loads for a probabilistic structural analysis.

The knowledge-based system approach used for the composite load spectra project provides an ideal environment for incremental development. The intelligent database paradigm employed in developing the expert system provides a smooth coupling between the numerical processing and the symbolic (information) processing. Large volumes of engine load information and engineering data are stored in database format and managed by a database management system. Numerical procedures for probabilistic load simulation and database management functions are controlled by rule modules. Rules were hard-wired as decision trees into rule modules to perform process control tasks. There are modules to retrieve load information and models. There are modules to select loads and models to carry out quick load calculations or make an input file for full duty-cycle time dependent load simulation. The composite load spectra load expert system implemented today is capable of performing intelligent rocket engine load spectra simulation. Further development of the expert system will provide tutorial capability for users to learn from it.

I. Objective and Approach

The objective of the composite load spectra (CLS) program under the sponsorship of NASA Lewis Research Center (LeRC) (Ref. 4) is to develop generic load models to simulate loads that are induced in space propulsion system components. Representative engine components that are considered in the study are transfer ducts, turbine blades, liquid oxygen (LOX) posts and engine system ducts. The simulated loads from the CLS load models are being compared to available test results and other analysis results. These probabilistic loads are needed in the probabilistic structural analyses for load effect and perturbation study. They are used primarily as input loading for the probabilistic structural analysis methodology (PSAM).

Current load analysis methodologies use deterministic models. Conservative bounding techniques are applied in load analyses and design. The design can be very conservative as a result of superposition of several individual bounding loads. In other cases there is insufficient information available to define realistic bounding loads and their variations. Measurement of loads and responses internal to hardware are very difficult due to a combination of high pressures, temperatures, flowrates and pump speeds. The probabilistic method allows a rational approach for quantifying these uncertain loads. They can then be utilized for structural response and reliability evaluations during the design phase. Probabilistic design analysis can help to locate the problem areas and allow cost-effective trade-offs to reach design goals.

Probabilistic load synthesis demands sophisticated methodology and modeling. It requires knowledge of state-of-the-art space propulsion system load analysis and calculation tools. These analyses and calculations involve intensive numerical processing. The load synthesis also demands knowledge on the engine model that determines pressures, temperatures, and flows and the load information. Management of the load information becomes an important issue.

The end product of the CLS program is a system that can help engineers generate loads on components from a set of primitive variables and their uncertainties based on previous historical information or expert opinion on expected variations. The system provides load information and data conveniently to the users and provides expertise in load evaluation.

These objectives point to a knowledge-based system (Ref. 3 and 9) approach that can provide knowledge of the space propulsion system and component loads and provide expertise in probabilistic methodology and load simulation. The knowledge-based system should be a coupled system for symbolic and numeric processing, should be able to manage a large volume of load information and data, should provide easily accessible information to users, and needs to be user friendly so that nonexpert users can use and learn from it.

The knowledge-based system approach has the facilities to encompass the knowledge of the space propulsion system and its loads, the numerical databases for load parameters, and load evaluation procedures. In addition, the knowledge-based system environment allows incremental development and modularization of the knowledge. Modules of knowledge (e.g., the load model, load data, or load calculation procedures) can be implemented and readily available to other modules.

The knowledge-based system built for the CLS program is an intelligent database system. The engine load models and load information such as the load distribution parameters (mean and coefficient of variation, and distribution type) are stored in database format. Rule modules in decision tree format are implemented to provide intelligence to the system to perform consultation, data retrieval and preparation of data for load simulation evaluation. Successful implementation of the basic system and experimentation with it has been accomplished in the last few years. It has demonstrated that an intelligent database system is one of the most appropriate approaches for an engineering knowledge-based application such as the CLS program.

Application of the CLS technology to synthesize component loads for the four sample components has been completed. The component loads were generated in the form of correlation fields accounting for the component load variations caused by the uncertainties of various engine parameters and engine inlet operation conditions. The component loads thus generated were utilized in the probabilistic structural analyses of the turbine blade (Ref. 6), the LOX post (Ref. 7), and high-pressure ducts (Ref. 1). Figures 1 and 2 depict the processes and analyses that are involved in the probabilistic structural analysis of the turbine blade. Figure 1 shows the process of applying the CLS technology to synthesize the turbine blade loads. Figure 2 shows how these loads are used in the probabilistic structural analysis process using the NESSUS (Nonlinear Evaluation of Stochastic Structures Under Stress) code (Ref. 8).

II. Engine Load Model and Load Databases

A space propulsion system is sophisticated and complex. Major subsystems typically include the main injector and combustion chamber, the nozzle, the high-pressure turbopumps, the low-pressure turbopumps, the ducts and pipings, and the control systems and valves. Figure 3 is a typical schematic showing these components. In the center are the main injectors, the combustion chamber and the nozzle. On the left are the low-pressure fuel turbopump (LPFTP) and the high-pressure fuel turbopump (HPFTP) that are interconnected to the rest

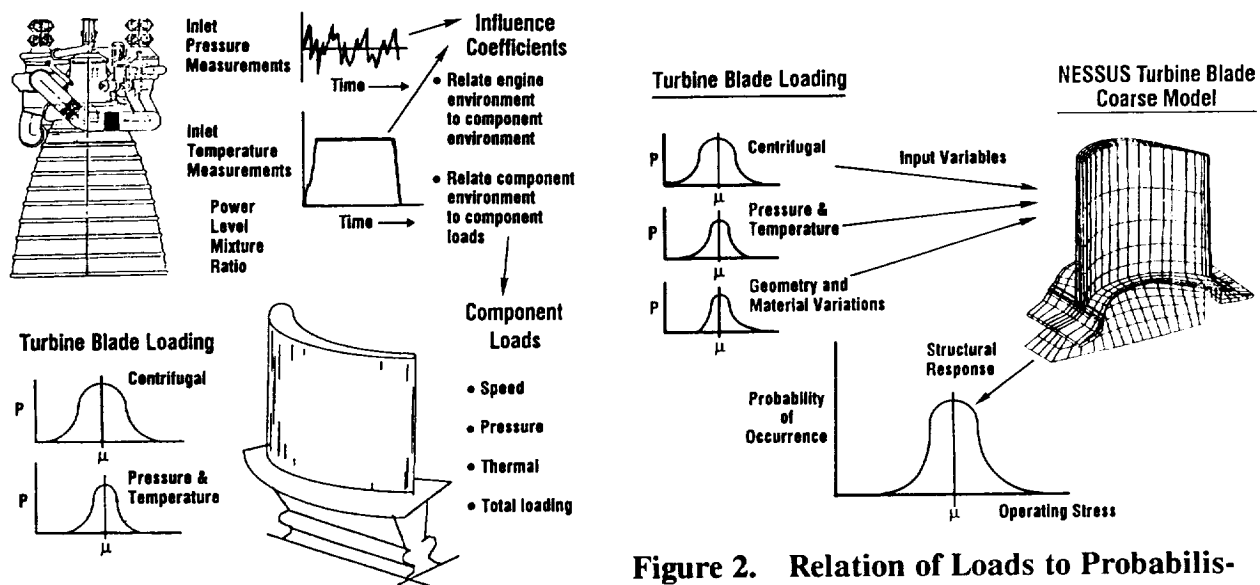


Figure 1. Typical Load Process

Figure 2. Relation of Loads to Probabilistic Structural Response Analysis

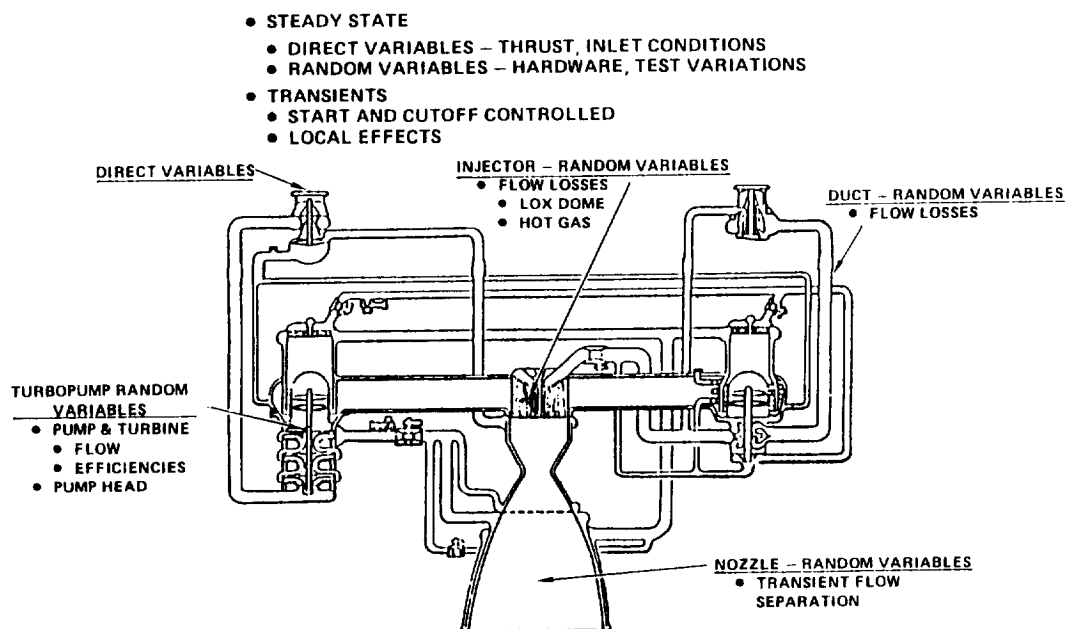


Figure 3. Typical Engine Schematic

of the engine by a series of ducting. On the right are the low-pressure oxidizer turbopump (LPOTP), the high-pressure oxidizer turbopump (HPOTP) and similar ducting.

The engine model implemented for the CLS is a numerical abstraction of the engine accounting for load variations as caused by various engine parameters and inlet conditions. It is a multilevel engine model as shown in Figure 4, which has been developed using a baseline engine model. The multilevel engine model is composed of the engine system influence model and various component load models. The engine system influence model is the foundation of the multilevel engine model, which allows various component load models to be built on it. The engine system model evaluates system performance variables and engine subsystem

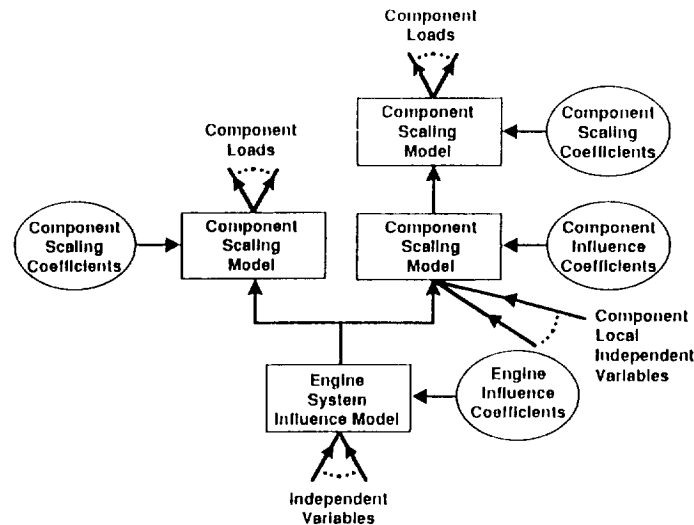


Figure 4. CLS Engine Model

operation loads (both types classified as system dependent loads) based on the engine operating power level, engine hardware and operating parameters (the engine hardware and operating parameters are classified as system independent loads). The component load models evaluate loads local to a component (classified as component loads) using the system loads as the component boundary loads (subsystem interface operating loads). Details of this model are reported in Reference 4.

The component load models are at the higher level of the multilevel engine model. The engine influence model calculates system interface variables based on engine performance. These system interface variables (e.g., turbine inlet pressure and temperature, and the turbine speed) provide the operating condition loads for the component load models to evaluate the component loads (e.g., the turbine blade nodal pressures and temperature, and the turbine blade centrifugal force).

The component load models are developed using several techniques and algorithms depending on the load type and the component. The general techniques include scaling and the probabilistic influence method. Scaling models include direct scaling with the system variable (e.g., the simple case of the turbine centrifugal force which is directly proportional to the square of the turbine speed) and the indirect scaling with a reference nodal load profile (e.g., those utilized in the turbine blade component pressure and temperature load models). The scaling technique is also used in normalized power density spectra for the fluctuation pressure loads and vibration loads. The probabilistic influence method is utilized in the component thermal load models. The probabilistic component load models retain the detailed deterministic analytical information inherent in the reference case analyses and yet provide a powerful algorithm to analyze the variations on different engine performance and operating conditions.

III. Probabilistic Methodology and Probabilistic Models

Probabilistic tools are required to generate the probabilistic engine loads (Ref. 5). The probabilistic methods available in the CLS expert system are (1) the Gaussian moment method, (2) RASCAL (Ref. 3), and (3) Monte Carlo. The Gaussian moment method is a moment propagation method which assumes that all of the load variables and engine parameters are normally distributed. The method referred to as the Quick Look Model (QLM) provides a fast, efficient method for determining the composite load distribution, if the basic variables' distributions are not severely skewed. The RASCAL method is a variance of the Discrete

Probability Distribution (DPD) method. Instead of combining all possible values, a Random Sampling Condensation Algorithm (RASCAL) was developed to handle the combination of random variables. The advantage of this method is that it is capable of handling standard distributional forms (e.g., normal, lognormal, Weibull, etc.) and nonstandard forms such as bimodal, and provides a range of levels for accuracy. This method can also be used to perform importance sampling, which can be used to examine regions of concern for the composite loads. Finally, the Monte Carlo method is also available. The Monte Carlo method can generate distributions with high accuracy and can calculate confident limits to assess the accuracy of the predicted loads.

The engine loads experience three phases of operation during a mission: the engine start transient, the steady-state operation and the cutoff transient. The probabilistic tools required for load simulation must include probabilistic models that can handle transient states. For slowly varying loads, a quasi-steady-state approximation is provided. For transient loads with large fluctuation, the transient spike model and spike arrival model are available. A rare event model is also available to simulate a low probability event such as "pop," an internal detonation caused by uneven burning. These probabilistic tools are available to be called upon by the load calculation module or other rule modules for transient load synthesis.

IV. The Load Expert System: LDEXPT Version 3.0

The load expert system, LDEXPT version 3.0, was implemented on NASA LeRC's mainframe computer. The structure of the system is shown in Figure 5. The load expert system has a rule-based module (RBMS) and a knowledge-based module (KBMS). The rule-based module has the user interface system SESUIM, which takes care of the user query and answer functions. The rule-based driver controls the overall processing of running a user selected rule module, performing a load calculation with the ANLOAD module, etc. The knowledge-based module has a database system, a duty cycle data processing module and a file I/O module. The database system manages the knowledge base and takes care of database functions such as database retrieval and update. The file I/O module performs file input and output to the operating system.

The Knowledge Base

The domain knowledge for the probabilistic engine load synthesis of a space propulsion system consists of two main areas: the probabilistic methodology and modeling, and the rocket engine structural load information and evaluation. The probabilistic methods and calculation are implemented on the load expert system with the traditional algorithmic and procedural codes. These coding routines are included in the load calculation module ANLOAD. The load information and the load model information are implemented in the knowledge base. The information of the knowledge base is utilized and processed by the rule modules.

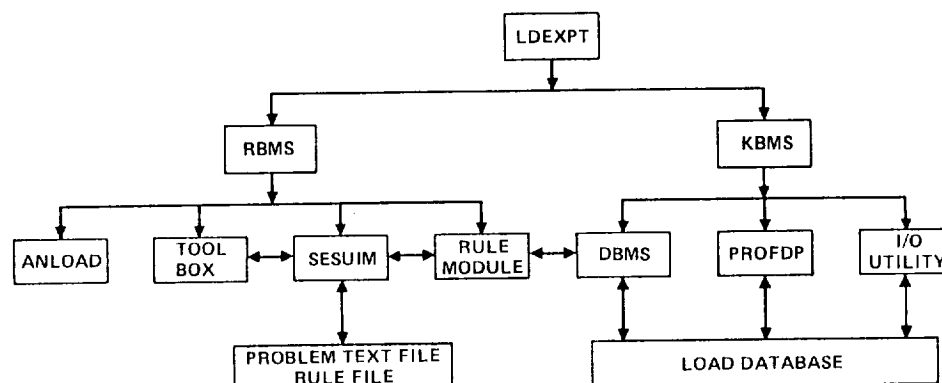


Figure 5. CLS Load Expert System

The synergism of the two knowledge domains and the coupling of the symbolic and numeric processing are brought about to shape a successful knowledge-based system for the CLS project.

The knowledge base of the load expert system is managed by the database system. The knowledge base has engine parameter information represented by their distribution parameters and distribution types (Figure 6). Data on the 64 system independent parameters, 99 system dependent parameters and numerous component loads are included. Their mean values, coefficients of variation and distribution type are stored in the knowledge base in database format. The influence coefficient set for the engine influence model also resides on the knowledge base.

The knowledge base also includes the information on the component load models available for each space propulsion component implemented on the system. Figure 7 lists some of the component load models implemented into the CLS knowledge base. The load dependency and scaling information of the component load models, the duty cycle data information, and component geometry information, etc., are required and included in the knowledge base. Much of the information is numerical. A rule-based system without a link to a database would have a difficult time managing the knowledge base. A dump database system would also have difficulty in handling the knowledge.

In addition to this, some of the knowledge includes the variations of the engine loads categorized as engine-to-engine variation, test-to-test variation and time slice-to-time slice (within a test) variation. The start transient event time line for a typical engine is delineated in Figure 8 for the first 4 seconds of a mission. The timing and operation of these events are critical in order to meet the stringent engine start transient thrust requirements. The best representation of the knowledge and how it would fit into the existing knowledge base is a task we are addressing at this time.

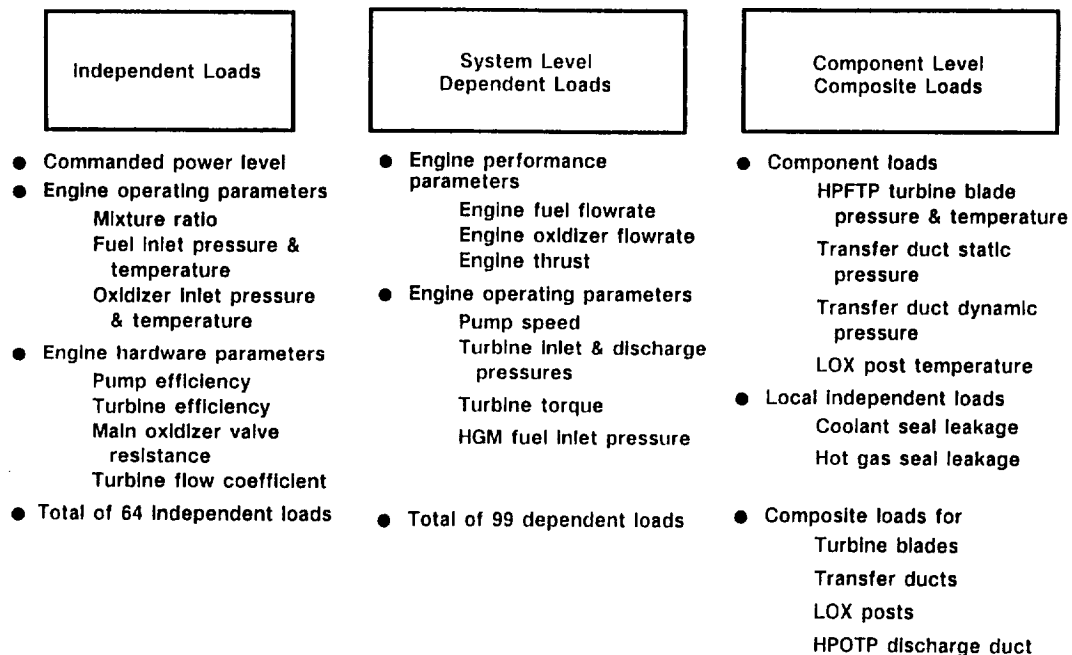


Figure 6. CLS Loads Knowledge Base

Engine System Model	Component Load Models
<ul style="list-style-type: none"> • Load distributions <ul style="list-style-type: none"> Means Coefficients of variation Distribution types Nominal value coefficients • Probabilistic Influence model <ul style="list-style-type: none"> Influence coefficients 1 σ gain values 	<ul style="list-style-type: none"> • Generic static pressure scaling model • Generic probabilistic thermal load model • Generic turbine blade pressure load model <ul style="list-style-type: none"> Tip, mean & hub cross section pressures Turbine blade pressure Interpolation scheme • HPFTP 2nd stage turbine blade pressure & temperature loads <ul style="list-style-type: none"> 2519 nodes geometry model Reference nodal pressures & temperatures • Turbine blade dynamic pressure load model • Duct dynamic pressure load model <ul style="list-style-type: none"> Transfer ducts, LOX posts, HPOTP discharge duct • Transient LOX post thermal load model • Vibration model

Figure 7. CLS Load Models Knowledge Base

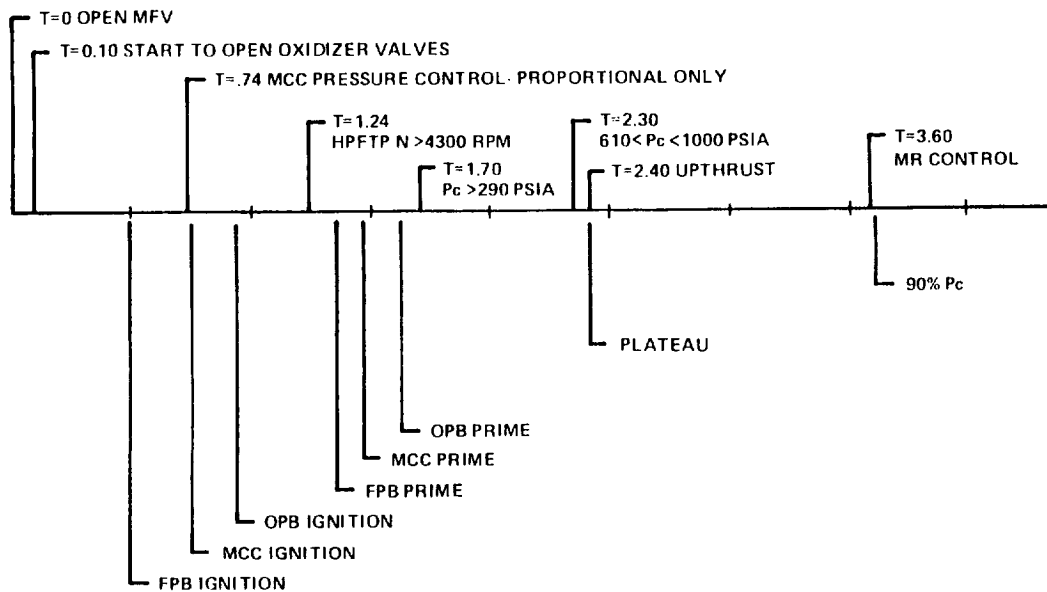


Figure 8. Engine Start Event Time Line

Validation and Verification

Validation and verification of the CLS expert system are essential to the success of the project. Validation of the correctness of the three implemented probabilistic methods and various models was carried out with makeup sample cases. The results of the case studies show that the three probabilistic methods (the Gaussian moment method, the RASCAL and the Monte Carlo method) and the various models perform as expected.

Verification of the CLS engine influence model and uncertain independent variables was performed by comparing the CLS results with those of the deterministic limit study of independent variables using measured data. Table 1 lists the results of the limit study. The results calculated by CLS agree with these results except those for the pump cavitation. Further investigation is in progress to improve our model. Verification of the load calculation was also performed by comparing the CLS calculations with the 10 second averaged database from the flight data and test data. In this study, only the effects of the following five independent vari-

Table 1. The Deterministic Limit Study Results

Independent Variable	Variation Ground Test	Difference	HPOTP Speed		HPFTP Speed		HPFTP Turbine Temperature		HPFTP Turbine Torque	
			Gain Effect	COV	Gain Effect	COV	Gain Effect	COV	Gain Effect	COV
Mixture Ratio	5.94 Min 6 Nom 6.06 Max	-0.06 0.06	-79.11 79.11	0.000938	138.402 -138.402	-0.00131	9.936 -9.936	-0.00180	105.81 -105.81	-0.00360
Fuel Inlet Pressure	20 Min 30 Nom 45 Max	-10 15	-0.59 0.885	0.000008	50.58 -75.87	-0.00074	4.25 -6.375	-0.00096	-13.34 20.01	0.000568
Oxidizer Inlet Pressure	23 Min 100 Nom 160 Max	-77 60	158.851 -123.78	-0.00167	16.016 -12.48	-0.00016	-9.471 7.38	0.001533	7.469 -5.82	-0.00022
Fuel Inlet Temperature	37 Min 37 Nom 40 Max	0 3	0 -5.55	-0.00003	0 679.335	0.004028	0 46.575	0.004238	0 113.49	0.001934
Oxidizer Inlet Temperature	163 Min 164 Nom 171 Max	-1 7	-58.07 406.49	0.002754	-2.77 19.39	0.000131	1.58 -11.06	-0.00115	-1.29 9.03	0.000175
Cavitation HPOTP	0 Min 0.02 Nom 0.08 Max	-0.02 0.06	-163.576 490.728	0.003879	-7.784 23.352	0.000184	4.608 -13.824	-0.00167	-3.632 10.896	0.000247
LPFTP Nozzle Area	0 Min 5 Nom 20 Max	-5 15	0.785 -2.355		-5.365 16.095		-6.8 20.4		-1.135 3.405	
Min Increment			-433.031		-242.671		-57.466		-131.027	
Max Increment			1130.414		804.768		81.446		143.491	
Individual Variation 3 Sigma			438.4848		579.6615		105.7691		415.1440	
Nom			28108		35131		1831.5		9779.6	
Max			29676.89		36515.42		2018.715		10338.23	
Min			27236.48		34308.66		1668.264		9233.428	
Gain %			8.682277		6.281523		19.13460		11.29704	
COV			0.014470		0.010469		0.031891		0.018828	

COV – coefficient of variation

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ables were considered: the commanded mixture ratio, the fuel inlet pressure, the oxidizer inlet pressure, the fuel inlet temperature and the oxidizer inlet temperature. A few of the results are presented here. Figure 9 shows the calculated cumulative distribution functions (CDFs) for the LOX mass flowrate by the RASCAL method and the Monte Carlo method together with the engine flight and test data. Figure 10 presents the result for the high-pressure oxidizer turbine (HPOT) discharge temperature. In all cases, the calculated CDFs fit well or close to the engine flight data and not very well with the test data. This is to be expected because the five independent variables have significant effects on engine performance, whereas the engine hardware parameters are dominant during tests whose effects were not included in the calculation. These engine-to-engine variation effects are apparent from the step shift in the CDFs of the test data.

V. Summary

The development of the CLS technology is evolving. The composite loads synthesized by CLS have been successfully applied to the probabilistic structural analyses of the SSME turbine blade, the HPOTP discharge duct and the LOX post. The knowledge-based system

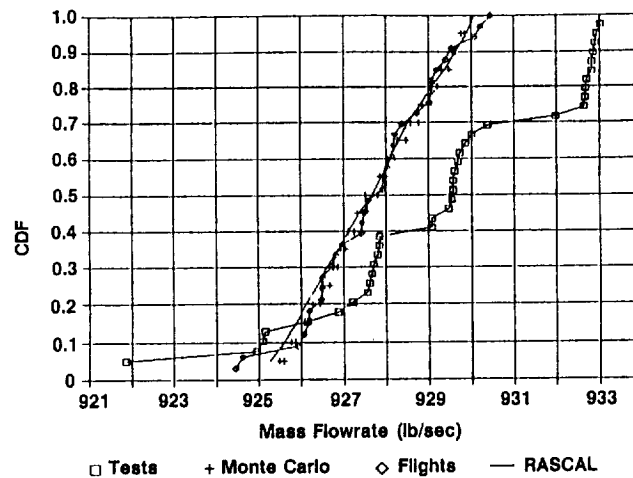


Figure 9. LOX Mass Flowrate Comparison (104% Power 10 Second Database)

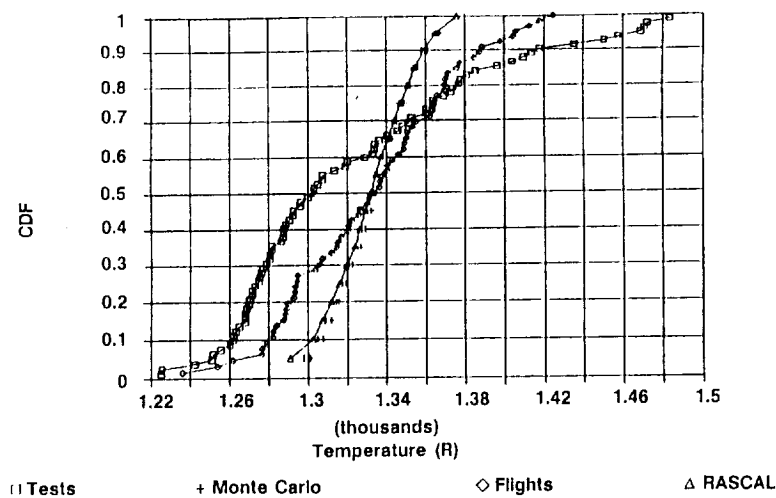


Figure 10. HPOT Discharge Temperature Comparison (104% Power 10 Second Database)

approach has provided an ideal environment for incremental development and modularization of the CLS system.

The intelligent database format has provided the crucial link between the engineering data and information and the decision tree inferencing. Most importantly, the knowledge and expertise of the Rocketdyne engineers on space propulsion system design, operation and analysis have made this a feasible research project.

The CLS expert system requires further development in areas such as making the CLS expert system more user friendly and making it a tutorial system that provides guidance to engineers in load synthesis.

The CLS has advanced the technology of the space propulsion system probabilistic load simulation. Correlation field approach is developed and being tested. Deeper understanding of engine flight and test data is evolving from the project. We are looking forward to more applications of the CLS technology to the probabilistic structural analysis, the structural reliability evaluation and life prediction of the space propulsion system components.

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